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SUMMARY

Experiments were performed to evaluate the effect of a swirler-mounted mixing venturi on the emissions and stability of six headplate modules in a flame-tube combustor. Unburned hydrocarbons, carbon monoxide, and oxides of nitrogen were measured for three types of fuel injectors both with and without a mixing venturi. Tests were conducted using Jet A fuel at an inlet pressure of 0.69 megapascal, an inlet temperature of 478 K, and an isothermal static-pressure drop of 3 percent. Oxides of nitrogen were reduced by over 50 percent with a mixing venturi with no performance penalties in either other gaseous emissions or pressure drop.

INTRODUCTION

An experimental investigation was conducted to determine the effect of a swirler-mounted mixing venturi on the emissions of a flame-tube combustor. The primary zone equivalence ratio was varied from the lean blowout limit to near stoichiometric values.

Concern over air pollution has drawn the attention of government agencies and industry over the quantities of exhaust emissions produced by gas turbine engines. The NASA Lewis Research Center has initiated in-house research, university grants, and industry contracts to investigate and develop methods for reducing the levels of pollutants generated by gas turbine engines. Contracted efforts have shown the success of various methods of pollution control in full-scale combustor rigs and in experimental engines, as described in references 1 to 4. These fuel staged or variable geometry combustors have shown the ability to reduce emissions over the entire engine operating envelope of high bypass ratio turbofan engines with minimum operational or performance penalties.

Pollutant emissions from gas turbines are greatest under two extremes of operation. Unburned hydrocarbons and carbon monoxide are generated at idle and low power, and oxides of nitrogen at high power. In order to control the low power emissions, a near stoichiometric primary zone of long residence time is required; and at high power, a fuel-lean primary zone with reduced residence time is dictated.

This investigation was initiated to determine the optimum primary zone stoichiometry for six headplate modules thought to be suitable for use in a variable geometry

combustor. The primary zone stoichiometry was to be optimized for minimum carbon monoxide at idle conditions and minimum oxides of nitrogen at high power. The effect of a mixing venturi on oxides of nitrogen generation was investigated. Tests were conducted on six headplate modules consisting of a main swirler and three different fuel nozzles. Each fuel nozzle configuration was tested with and without the mixing venturi at an inlet pressure of 0.69 megapascal, an inlet temperature of 478 K, and an isothermal static-pressure drop of 3 percent. Primary zone equivalence ratios were varied from lean blowout to near stoichiometric.

APPARATUS AND PROCEDURE

Test Rig

The combustor was instrumented to record and monitor all necessary operating parameters. These data and the emission measurements were recorded by the facility digital data acquisition system. On-line computational capability provided rapid data reduction.

Figure 1 is a plan view of the test cell. The airflow rate was measured by using a square-edge orifice in accordance with ASME standards. Figure 2 is a cross-sectional view of the test section used to screen single headplate modules. The inlet air was heated to 478 K in a nonvitiating preheater. Fuel flows below 0.011 kilogram per second were measured by using a single turbine meter; for fuel flows above 0.011 kilogram per second, two turbine meters in series were used. Fuel pressure and temperature were measured upstream of the fuel injector. Inlet temperature and static pressure were measured upstream of the headplate. The swirler was mounted in a removable headplate in the 30-centimeter diameter duct, with a 9.1-centimeter diameter steam cooled combustion liner downstream. Eight thermocouples were affixed to the liner and steam was controlled to maintain the liner temperature above 1100 K when possible.

A single six-point gas sample probe was located 35 centimeters downstream of the headplate in the same plane as two four-point platinum - platinum-13-percent-rhodium thermocouple rakes and a static-pressure tap. Water was injected to cool the exhaust products, and a backpressure valve was used to control the rig pressure. The gas sample was transported to the gas analysis instrumentation by steam traced lines. The exhaust gas analysis system consisted of four commercially available instruments along with associated peripheral equipment necessary for sample conditioning and instrument calibration.

The total hydrocarbon content of the exhaust gas was measured with a Beckman Instruments model 402 flame ionization detector. Both carbon monoxide and carbon

dioxide were measured with Beckman Instruments model 315B nondispersive infrared analyzers. The concentration of oxides of nitrogen was measured with a Thermo Electron Corporation model 10A chemiluminescence analyzer. This instrument included a thermal converter to reduce nitrogen dioxide to nitrogen oxide. Data were obtained as total oxides of nitrogen (nitrogen oxide + nitrogen dioxide). Emission indices were based on metered fuel-air ratio and were calculated according to the procedures of reference 5.

Headplate Modules

The effect of the mixing venturi on three fuel injectors was determined. The injectors used were a simplex pressure atomizer, and two air-blast atomizers, a splash-groove injector and a simple splash-plate injector with a counterswirl insert. All were mounted in the same 45° blade angle main swirler.

Main swirler. - The main air swirler is shown in figure 3. It consisted of 14 flat blades inclined 45° relative to the airflow direction. This swirler was the same for all the configurations.

Mixing venturi. - The mixing venturi is shown in figure 4. It had a throat area equal to 175 percent of the main swirler flow area and a length from the swirler face to the throat equal to 28 percent of the throat diameter.

Simplex pressure atomizer. - The simplex nozzle used was a DeLavan model WDA-18.0, a hollow cone, 45° spray angle pressure atomizer, nominally rated at 0.017 kilogram per second at a 0.86 megapascal pressure differential.

Splash-groove injector. - The splash-groove injector is described in reference 6. Fuel is injected through 18 orifices into two grooved portions of the nozzle, as shown in figure 5. The fuel then either splashes off the cone or flows over the groove lip, where it is atomized by the airstream. This nozzle delivered 0.017 kilogram per second at a 0.028 megapascal pressure differential.

Splash-plate injector. - The splash-plate configuration resulted from replacing the injector assembly with a counterrotating swirler and a 0.5-centimeter fuel tube, as shown in figure 6. A splash plate 0.5 centimeter in diameter was attached to the tube. The fuel was atomized by the airstream as it flowed over the lip of the splash plate. The counterrotating swirler insert had 10 blades inclined 45° relative to the airflow direction. Its flow area was 14 percent of the main swirler flow area. This nozzle delivered 0.017 kilogram per second at a 0.017 megapascal pressure differential.

Flow Calibrations

The main swirler and main swirler plus the counterswirl insert were flow calibrated under ambient conditions in an atmospheric exhaust calibration stand.

The flow area for a flat blade swirler of sufficient thickness to produce blade overlap is approximated by

$$A = \frac{\pi}{4} (D^2 - d^2) \cos \alpha - \frac{NT}{2} (D - d)$$

where

- A swirler flow area, cm^2
- D swirler flow passage outside diameter, cm
- d swirler flow passage inside diameter, cm
- α swirler blade angle relative to normal flow direction, deg
- N number of swirler blades
- T blade thickness, cm

This area term can be substituted into the modified Bernoulli equation

$$\dot{w}_a = 0.1414 C_d A \sqrt{\rho \Delta p}$$

where

- \dot{w}_a air mass flow, kg/sec
- C_d flow coefficient
- ρ air mass density, kg/m^3
- Δp static-pressure drop, MPa

and a linear regression analysis can be done to determine the flow coefficient for a given swirler. Figure 7 shows the experimental data and the curve produced by this analysis. The discharge coefficient for the main 45° swirler was 0.75, and for the 45° counterswirl insert, it was 0.74.

RESULTS AND DISCUSSION

Emissions Measurements

Simplex pressure atomizer. - Figure 8 depicts the two headplate configurations tested with the simplex atomizer. Configuration 1a had the fuel nozzle mounted in the center of the main swirler; for configuration 1b, a mixing venturi was added to the basic configuration 1a. Figure 9 displays the oxides of nitrogen emission index, in grams of NO_2 per kilogram of fuel burned, as a function of the primary zone equivalence ratio for configurations 1a and 1b. The primary zone equivalence ratio was based on the total metered fuel flow and airflow to the rig according to the following equation:

$$\phi = \frac{\frac{\dot{w}_f}{\dot{w}_a}}{\left(\frac{f}{a}\right)_{\text{stoich}}}$$

where

ϕ	equivalence ratio
\dot{w}_f	total mass rate of fuel flow
\dot{w}_a	total mass rate of airflow
$(f/a)_{\text{stoich}}$	stoichiometric fuel-air ratio, 0.06817 for Jet A fuel (ref. 7)

The effect of the mixing venturi on the simplex atomizer was to reduce the oxides of nitrogen emissions evenly over the entire range of equivalence ratios. The rate at which the oxides of nitrogen increased with equivalence ratio was not changed.

The carbon monoxide emission index, in grams of carbon monoxide per kilogram of fuel burned, is shown in figure 10 as a function of equivalence ratio for configurations 1a and 1b. The effect of the mixing venturi was to create a broader minimum with a steeper rise under fuel-lean conditions. The dashed curve represents the equilibrium carbon monoxide concentration calculated from reference 8 for an inlet temperature of 478 K. This calculation, based on asymptotic chemical kinetics, predicts the minimum concentration of carbon monoxide possible for the given conditions. The presence of data below the equilibrium line indicates poor design or operation of the gas sample probe or equipment. In this case, the gas sample flow rate was excessive and possibly resulted in inadequate quenching of the sample gas for the tests on configuration 1b. This apparently allowed the sample gas sufficient time at a high temperature so that there was significant burnout of the carbon monoxide.

The unburned hydrocarbon emission index, in grams of CH_2 per kilogram of fuel burned, is shown in figure 11 as a function of equivalence ratio for configurations 1a and 1b. The mixing venturi had no noticeable effect on the production of unburned hydrocarbons for this nozzle.

The increase in oxides of nitrogen as equivalence ratio rose in both cases indicated a well-mixed system which avoids fuel-rich combustion and subsequent stoichiometric burning during dilution. The reduction in oxides of nitrogen and the increase in carbon monoxide production under fuel-lean conditions represented a more evenly mixed system with the mixing venturi. The unburned hydrocarbon emissions showed that the addition of the mixing venturi had no effect on the atomization process of this injector. This behavior is expected for a pressure atomizer whose atomization characteristics are generally independent of the system aerodynamics.

Splash-groove injector. - The two configurations tested with a splash-groove injector are shown in figure 12. Configuration 2a had the fuel nozzle centered in the main swirler, and configuration 2b had a mixing venturi added to configuration 2a. Figure 13 depicts the oxides of nitrogen emissions as a function of the equivalence ratio produced by the splash-groove injector both with and without a mixing venturi. This figure shows reduced oxides of nitrogen generation with the venturi for all equivalence ratios tested.

The effect of the venturi on carbon monoxide emissions is to produce approximately the same minimum with increased production under fuel-lean conditions, as shown in figure 14. An equilibrium carbon monoxide concentration is also shown, and for both configurations 2a and 2b all data are above equilibrium levels.

Figure 15 depicts increased unburned hydrocarbon production for all equivalence ratios for configuration 2b. This was probably due to fuel impingement on the walls of the mixing venturi, with subsequent shedding of large droplets off the exit lip.

The reduction in oxides of nitrogen and the increase in carbon monoxide production under extremely fuel-lean conditions are representative of the finer atomization, more complete vaporization, and better mixing obtained with the mixing venturi configuration. These conditions produced a more uniform fuel-air mixture for combustion, which resulted in lower peak flame temperatures.

Splash-plate injector. - Figure 16 depicts the two headplate configurations tested that utilized a splash-plate injector with counterrotating air swirlers. Configuration 3a consisted of this device mounted in the center of the main swirler, and configuration 3b had the mixing venturi added to configuration 3a. Figure 17 depicts the oxides of nitrogen production as a function of equivalence ratio for configurations 3a and 3b. The mixing venturi effected a reduction in oxides of nitrogen generation over the tested range of equivalence ratios.

The carbon monoxide emissions for configurations 3a and 3b are shown in figure 18.

A reduction by an order of magnitude was achieved near an equivalence ratio of 0.5 with the addition of the mixing venturi.

Unburned hydrocarbon emissions were reduced for the venturi-equipped configuration 3b above an equivalence ratio of 0.4, as shown in figure 19.

The effect of the mixing venturi on the splash-plate injector was to produce significant reductions in all gaseous emissions. In this injector, the atomization process, fuel-air mixing, and recirculation zone formation are all governed by aerodynamic forces. The presence of the venturi forces the swirling air cones to remain confined and thereby intensifies the shear layer produced by the counterrotating air swirlers. When large fuel droplets pass through this shear layer, they are shattered by the intense confined aerodynamic forces. This effect can be seen by the reduction of both unburned hydrocarbon and carbon monoxide emissions for this configuration.

Discussion

The minimum unburned hydrocarbon emissions were achieved with configurations 1a and 1b, which both include a simplex atomizer, a known good atomizer. The air-blast injectors used in this study, therefore, produced poorer atomization than the simplex atomizer. Ingebo achieved reductions in unburned hydrocarbons with the splash-groove injector relative to a pressure atomizer in the studies of references 6 and 9. His configuration was significantly different from those of this investigation in that the splash-groove injector was mounted in a venturi approximately two swirler diameters downstream of the swirler. This placement apparently produced a more intimate contact of the fuel film and the high-velocity airstream to give superior atomization with the splash-groove injector. Flow visualization on configuration 2a revealed the presence of reverse airflow across the injector groove lips, as shown in figure 20. The placement of a splash-groove injector at the swirler exit face does not provide the high-velocity airstream necessary for the operation of this injector and should, therefore, be avoided.

Postrun examination showed no thermal distress, carboning, or coking on any part of the mixing venturi during the test program. Figure 21 shows the results of visual inspections for carbon and coke after each run for configurations 1a, 2a, and 3a. Inspection of the configurations with mixing venturis showed the same general trends. The simplex atomizer configuration 1a had carbon buildup on the face of the simplex nozzle and coke accumulation on the remaining nozzle surfaces. This nozzle did not have an air shroud over the nozzle tip. The splash-groove injector configuration 2a developed carbon deposits on the splash-groove portion of the nozzle and on the flame side of the swirler blade roots. This was apparently caused by the aspiration of

fuel along the flow streamlines, as shown in figure 20. Coking was apparent on the faces of the injector exposed to the flame. The splash-plate injector configuration 3a had carbon deposits on the ring between the inner and outer swirlers and on the side of the inner swirl vanes exposed to the flame. It had coke deposits on the splash plate.

SUMMARY OF RESULTS

The effect of a swirler-mounted mixing venturi on the emissions of three types of fuel injectors was investigated at an inlet pressure of 0.69 megapascal, an inlet temperature of 478 K, and an isothermal static-pressure drop of 3 percent. In all cases, significant reductions in oxides of nitrogen emissions were achieved with the addition of a mixing venturi to the basic configuration.

The best configuration for minimum oxides of nitrogen production was a simplex pressure atomizer with a mixing venturi. The air-blast injectors investigated in this study apparently produced large fuel drops that were not as well mixed as the fuel sprays from the simplex atomizer.

The mixing venturi confined the swirling air cones and thereby enhanced fuel atomization, fuel-air mixing, and vaporization. These conditions produced a more uniform fuel-air mixture for combustion and thus lower peak flame temperatures and reduced oxides of nitrogen emissions resulted.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 5, 1978,
505-04.

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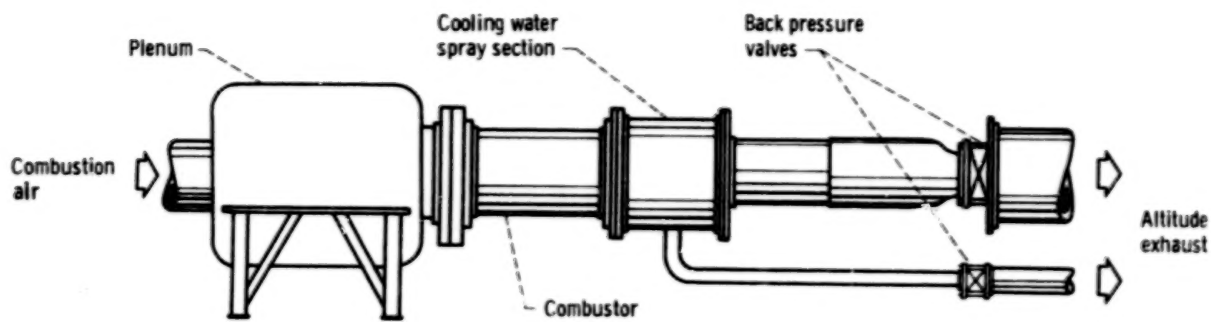


Figure 1 - Test facility.

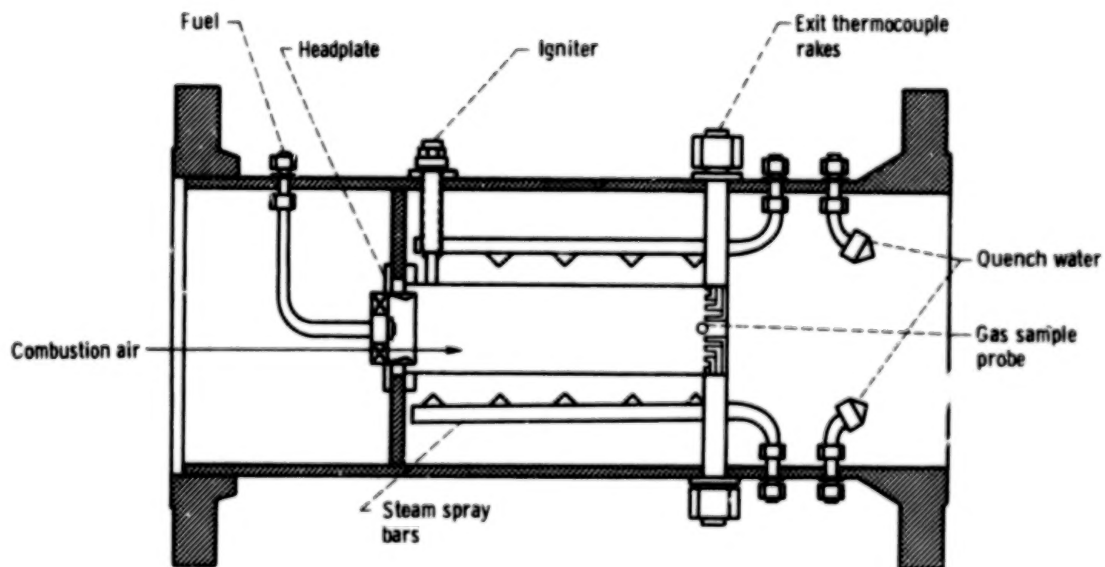


Figure 2 - Combustor test section for single headplate modules.

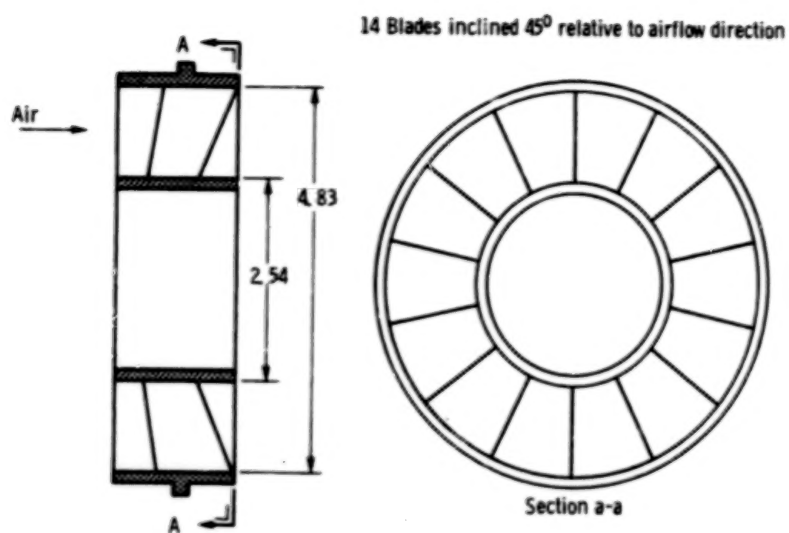


Figure 3 - Main air swirler. (all dimensions are in centimeters.)

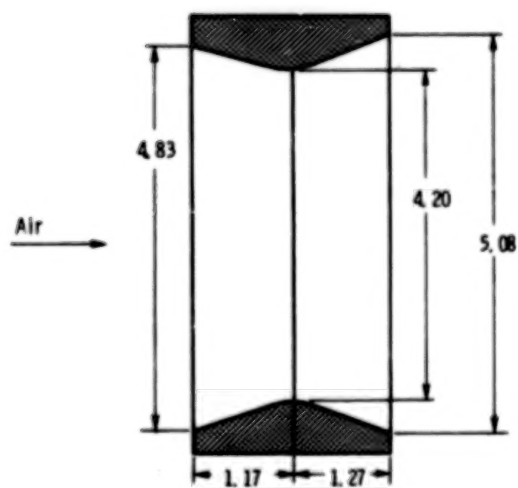


Figure 4 - Mixing barrel. (all dimensions are in centimeters.)

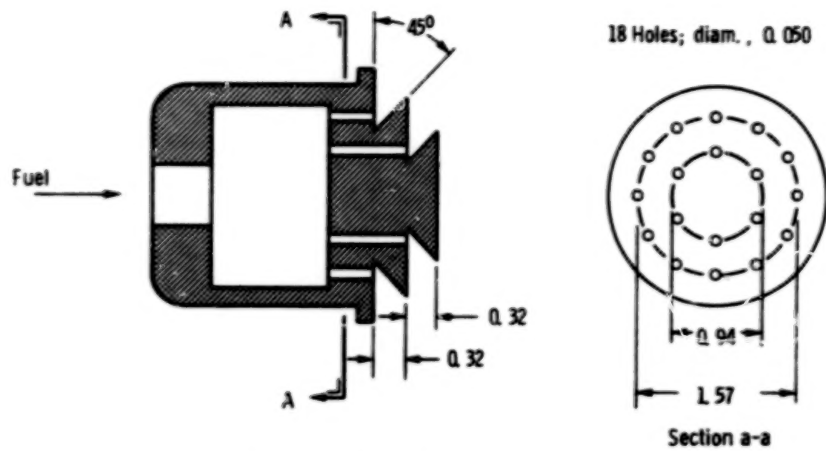


Figure 5. - Splash-groove fuel injector. (all dimensions are in centimeters.)

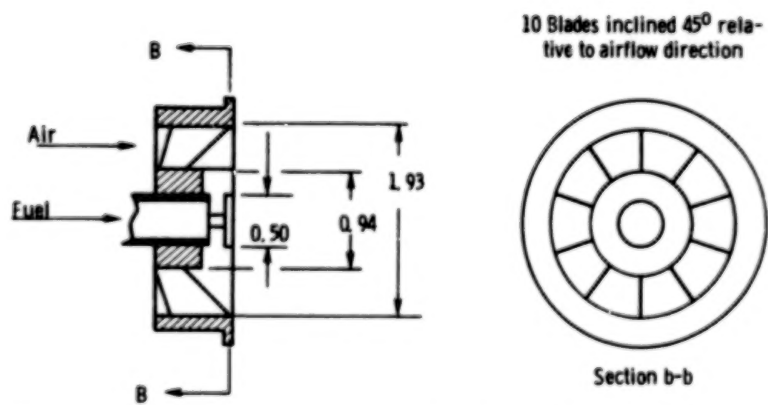


Figure 6. - Splash-plate fuel injector with counterrotating swirler. (all dimensions are in centimeters.)

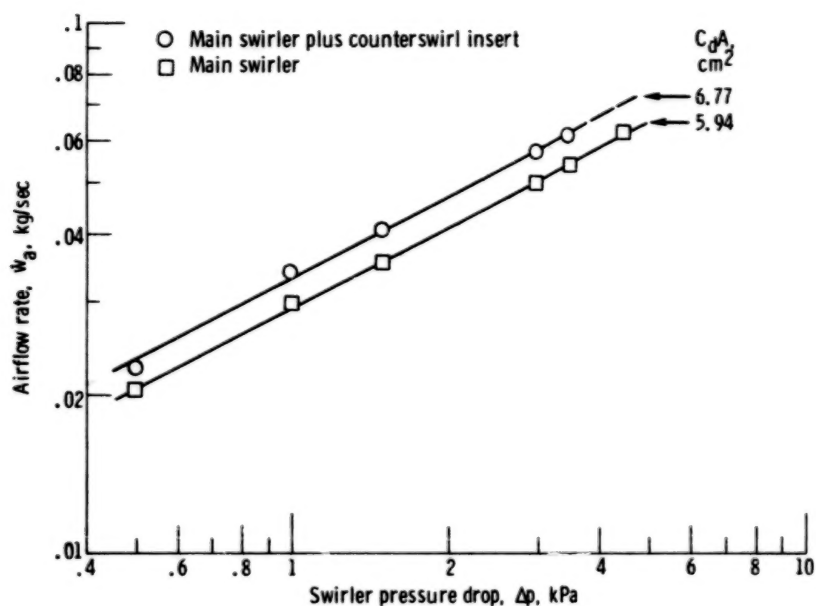


Figure 7. - Swirler flow calibrations. Inlet pressure, 0.1 megapascal; inlet temperature, 295 K.

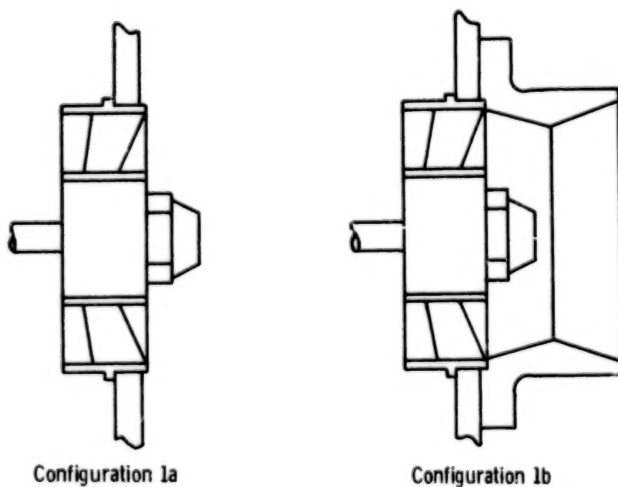


Figure 8. - Simplex pressure atomizer test configurations.

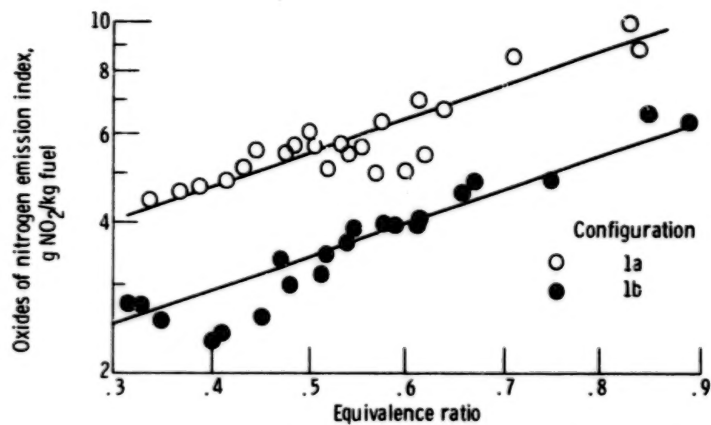


Figure 9. - Oxides of nitrogen emissions for configurations 1a and 1b. Inlet pressure, 0.69 megapascal; inlet temperature, 478 K; isothermal static-pressure drop, 3 percent.

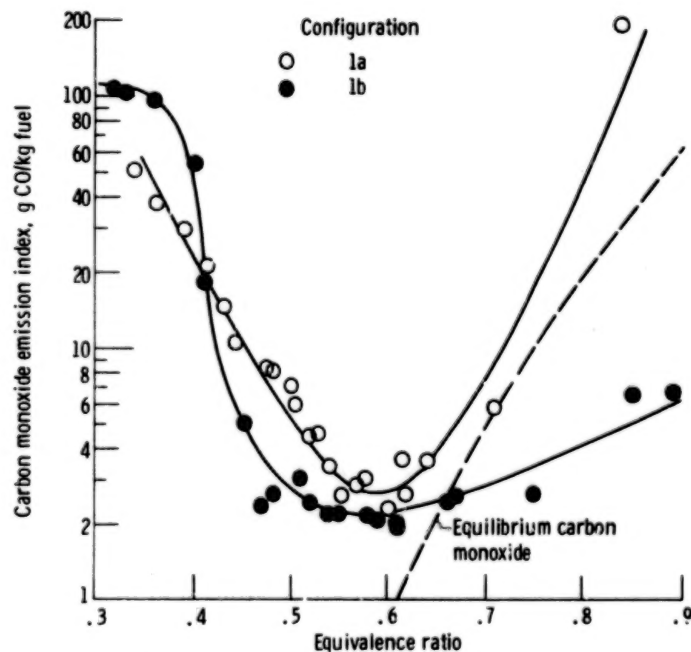


Figure 10. - Carbon monoxide emissions for configurations 1a and 1b. Inlet pressure, 0.69 megapascal; inlet temperature, 478 K; isothermal static-pressure drop, 3 percent.

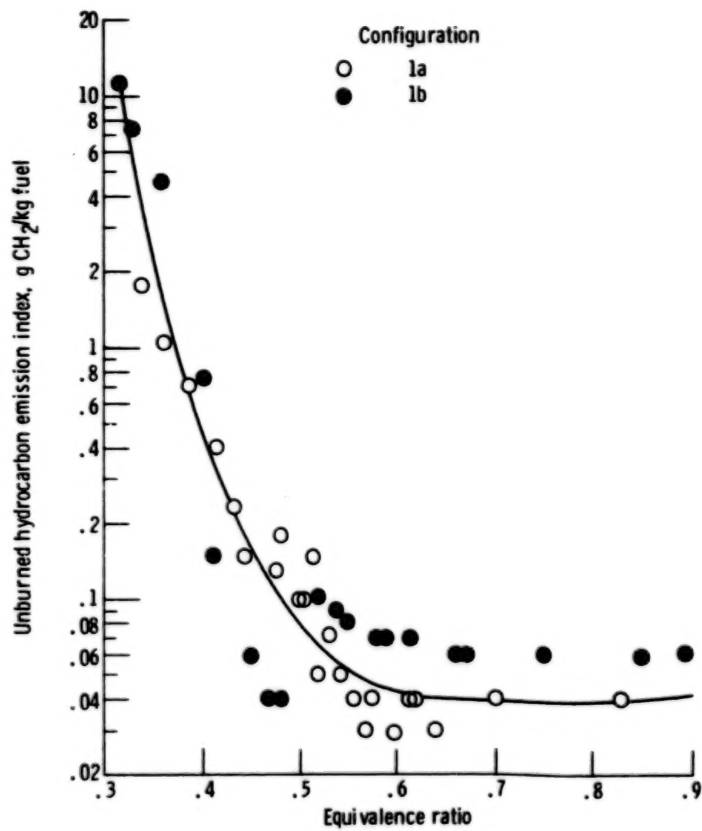


Figure 11. - Unburned hydrocarbon emissions for configurations 1a and 1b. Inlet pressure, 0.69 megapascal; inlet temperature, 478 K; isothermal static-pressure drop, 3 percent.

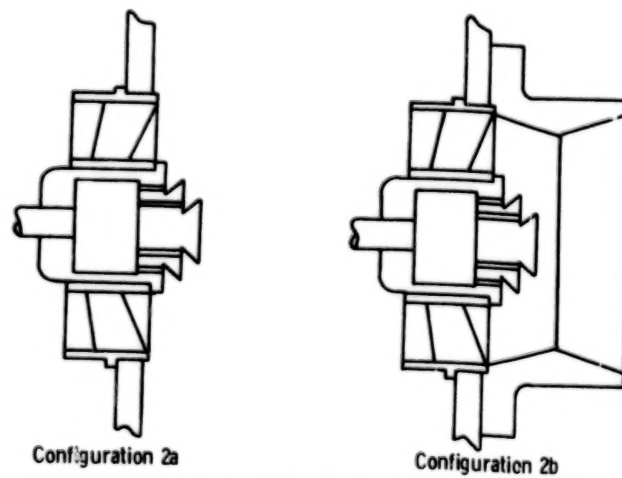


Figure 12 - Splash-groove injector test configurations.

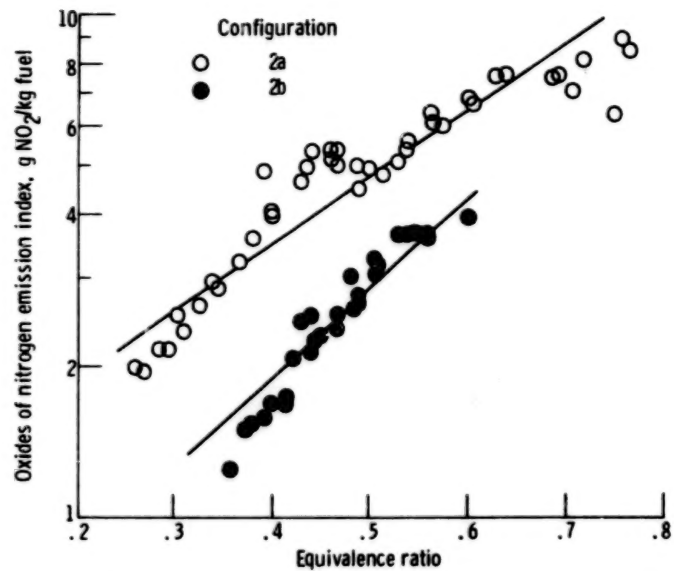


Figure 13. - Oxides of nitrogen emissions for configurations 2a and 2b. Inlet pressure, 0.69 megapascal; inlet temperature, 478 K; isothermal static-pressure drop, 3 percent.

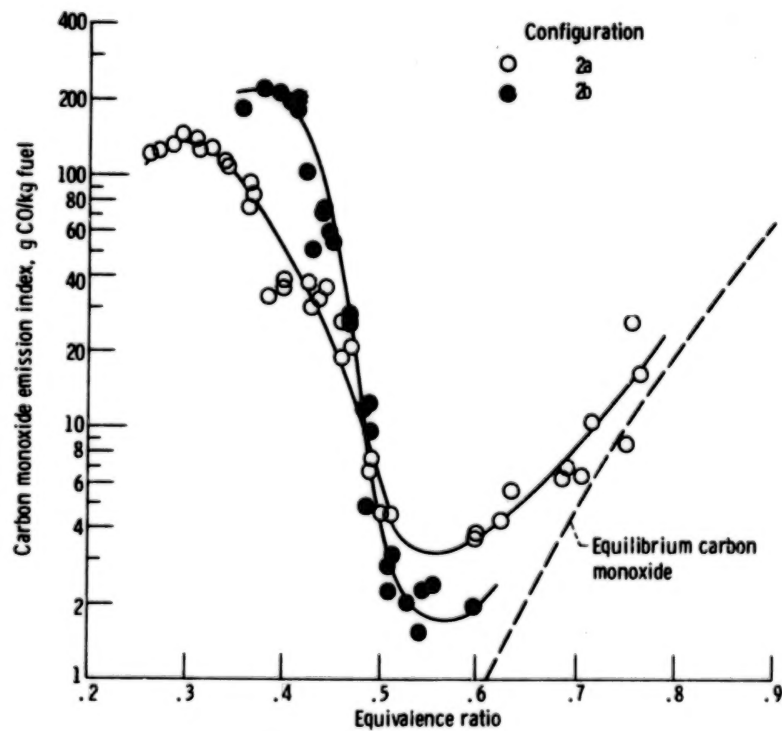


Figure 14. - Carbon monoxide emissions for configurations 2a and 2b. Inlet pressure, 0.69 megapascal; inlet temperature, 478 K; isothermal static-pressure drop, 3 percent.

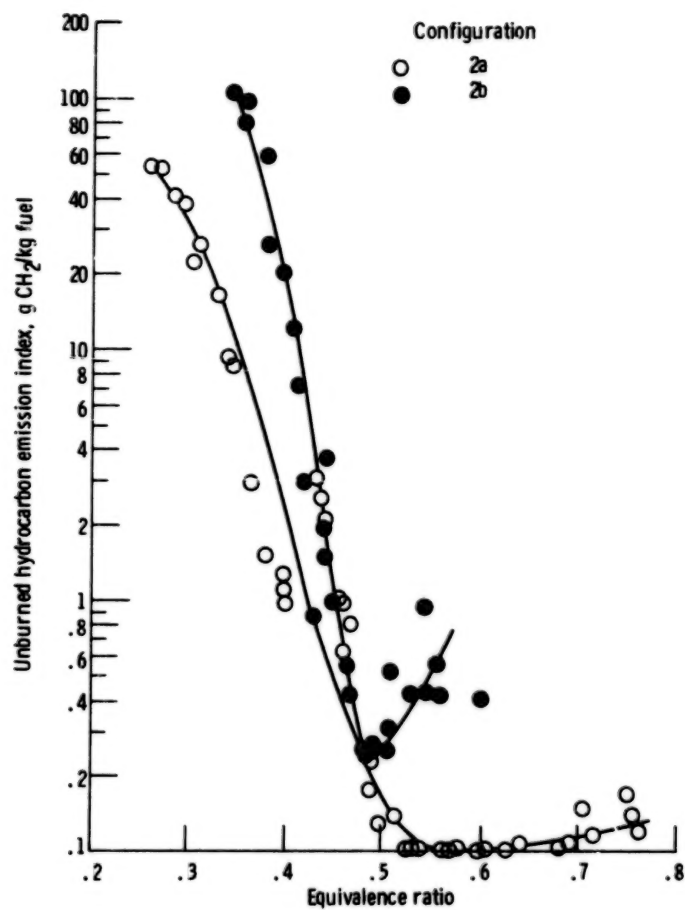


Figure 15. - Unburned hydrocarbon emissions for configurations 2a and 2b. Inlet pressure, 0.69 megapascal; inlet temperature, 478 K; isothermal static-pressure drop, 3 percent.

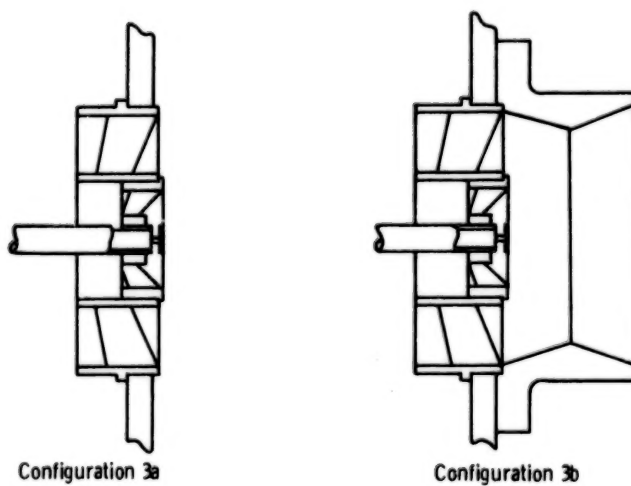


Figure 16. - Splash-plate injector test configurations.

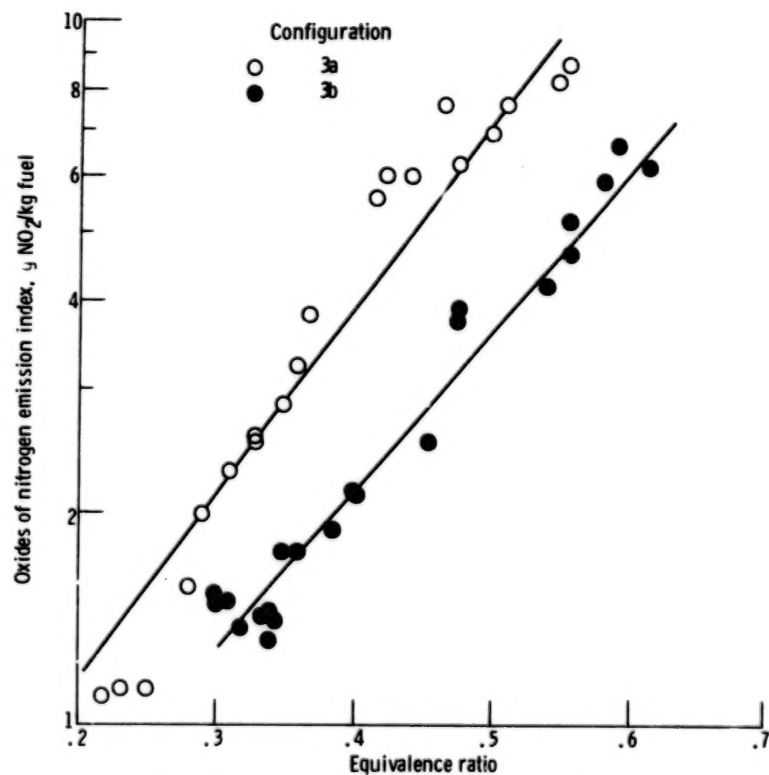


Figure 17. - Oxides of nitrogen emissions for configurations 3a and 3b. Inlet pressure, 0.69 megapascal; inlet temperature, 478 K; isothermal static-pressure drop, 3 percent.

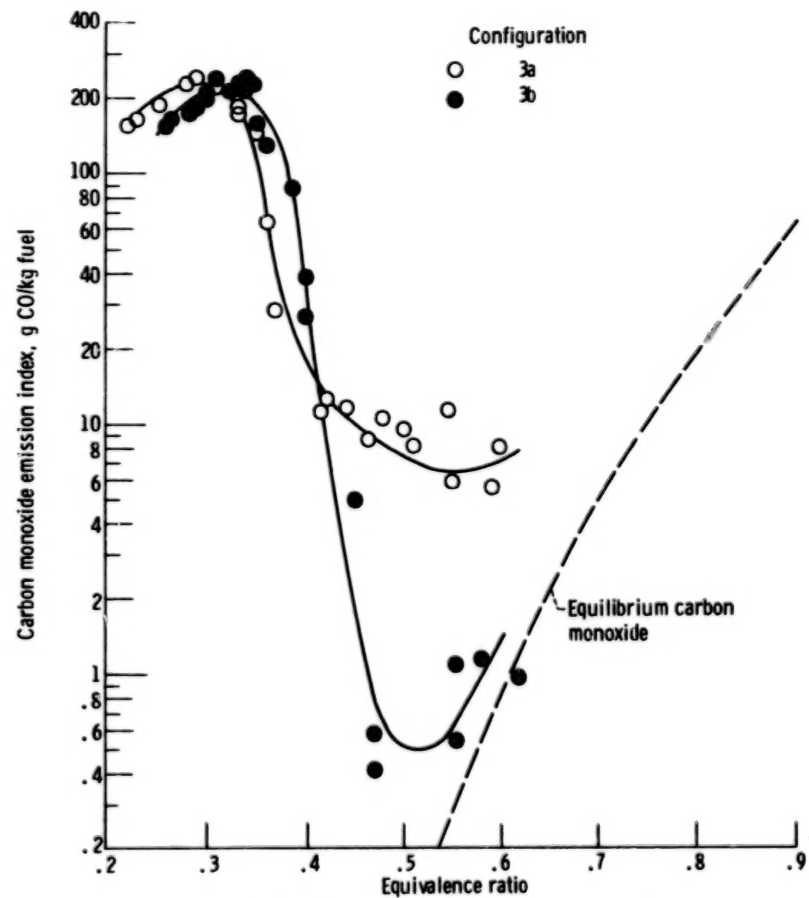


Figure 18. - Carbon monoxide emissions for configurations 3a and 3b. Inlet pressure, 0.69 megapascal; inlet temperature, 478 K; isothermal static-pressure drop, 3 percent.

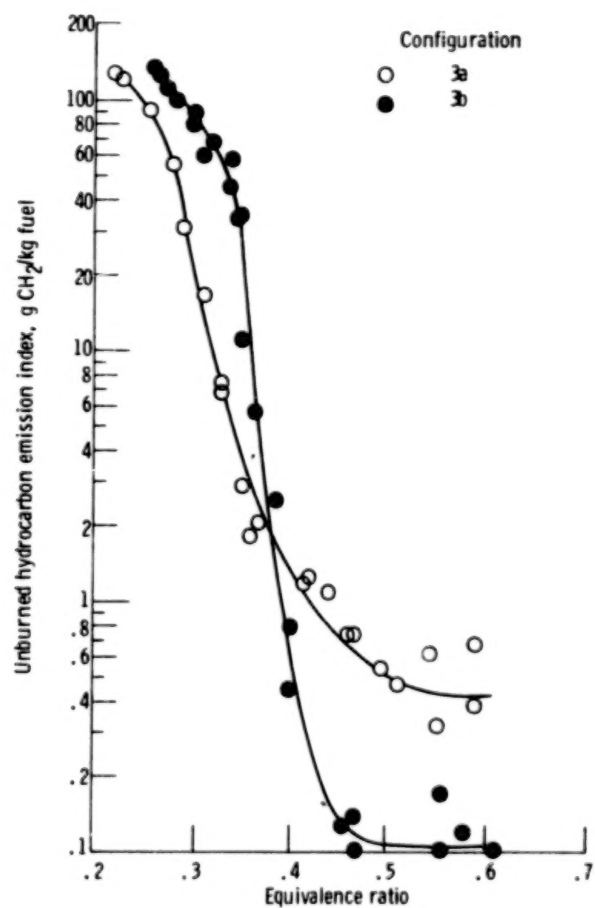


Figure 19. - Unburned hydrocarbon emissions for configurations 3a and 3b. Inlet pressure, 0.69 megapascal; inlet temperature, 478 K; isothermal static-pressure drop, 3 percent.

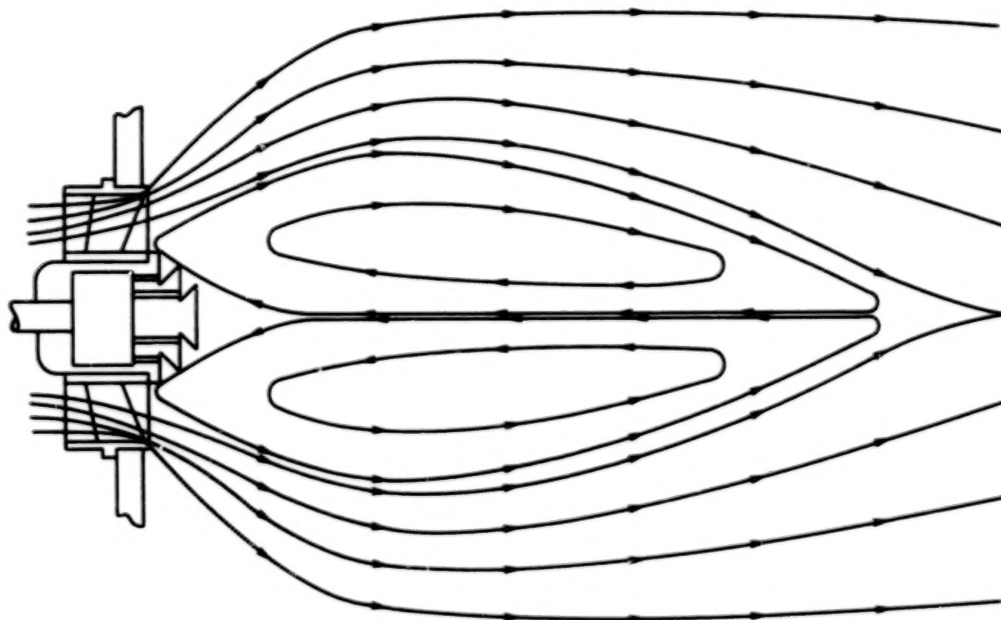


Figure 20 - Observed flow pattern downstream of headplate configuration 2a. Isothermal static pressure drop, 3 percent; ambient pressure and temperature.

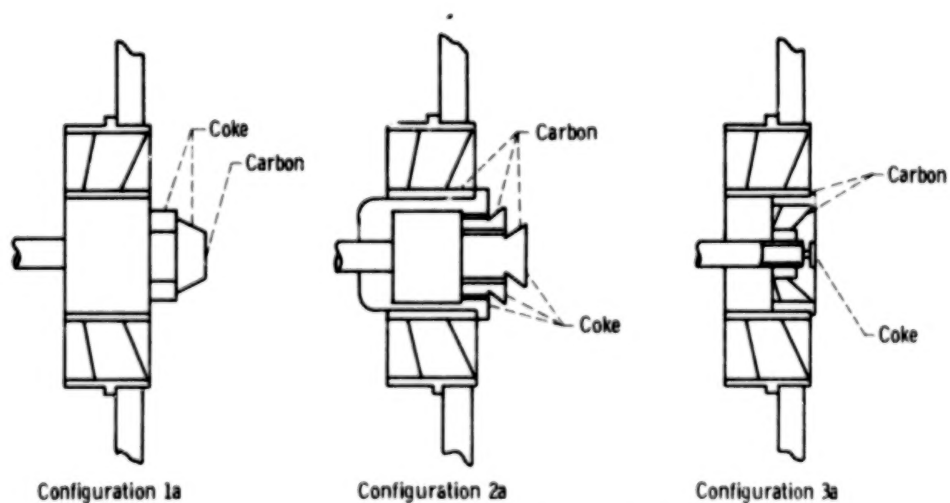


Figure 21 - Carbon and coke deposition on configurations 1a, 2a, and 3a.

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